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80-Gb/s Wavelength Conversion Based on Cross-Phase Modulation in High-Nonlinearity Dispersion-Shifted Fiber and Optical Filtering

Jianjun Yu and Palle Jeppesen

***Abstract*—Using cross-phase modulation in a 1-km high-nonlinearity dispersion-shifted fiber with subsequently filtering by a tunable optical filter, 80-Gb/s pulsewidth maintained wavelength conversion is realized. Penalty-free transmission over 80-km conventional single-mode fiber and 12-km dispersion-compensating fiber for 80-Gb/s converted signal is realized.**

***Index Terms*—High-nonlinearity fiber, nonlinear optical loop mirror, optical time division multiplexing, wavelength conversion.**

I. Introduction

WAVELENGTH conversion has been suggested as one of the key functions for wavelength-division-multiplexing (WDM) optical networks and photonic switch blocks. Recently, some high-speed wavelength conversion experiments have been reported [1]–[3]. In [2], 100-Gb/s wavelength conversion by use of a semiconductor optical amplifier (SOA)-based device and delay interference configuration was demonstrated, however, there is a relatively large power penalty after wavelength conversion of about 6 dB. The penalty is caused by a relatively long carrier lifetime of the SOA. Therefore, this kind of wavelength conversion can easily suffer from pattern effect and format conversion. In [3], 160-Gb/s wavelength conversion by use of periodically poled $LiNbO_3$ was realized; however, wavelength conversion based on FWM is polarization sensitive and the conversion effect is small when the wavelength spacing between the control pulse and CW lightwave is large. Wavelength conversion, based on cross-phase modulation (XPM) in a dispersion-shifted fiber (DSF), has the potential of attaining terabits-per-second switching operation due to the ultrafast optical nonlinearity.

The principle of using XPM in a DSF with subsequent filtering by a tunable optical filter to realize signal regeneration and wavelength conversion was put forward [4], [5] and experimentally demonstrated [6]. Its principle is: A continuous-wave (CW) lightwave is launched into the DSF along with the control signals. The control signals will modulate the CW lightwave and two sidebands on the CW lightwave will be generated. After suppression of the original CW wavelength, and filtering out one of the generated side-ands, the wavelength-converted

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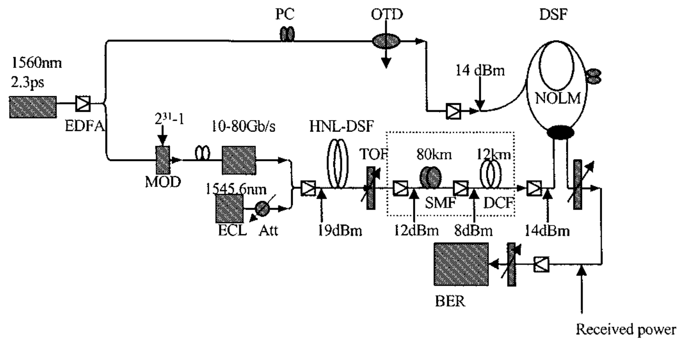

Fig. 1. Experimental setup for 80 Gb/s wavelength conversion and transmission. EFRL: erbium fiber ring laser, MOD: $LiNbO_3$ modulator, MUX: 10–80 Gb/s multiplexer, NOLM: nonlinear optical loop mirror, SMF: single mode fiber, DCF: dispersion compensating fiber, TOF: tunable optical filter, ECL: external-cavity laser, OTD: optical time delay, Att: attenuator.

signals can be obtained. The pulsewidth of the converted pulse based on XPM in the DSF is determined by the power of the control pulse, dispersion effect and walkoff time between the control pulse and the CW lightwave [7]. Broad-band pulsewidth-maintained wavelength conversion can be realized by use of a short highly nonlinear (HNL)-DSF because dispersion and walkoff effects can be reduced [8]. We recently reported on an 80-Gb/s pulsewidth-maintained wavelength conversion based on a HNL-DSF nonlinear optical loop mirror (NOLM) [9]. In this letter, we report 80-Gb/s pulsewidth-maintained wavelength conversion based on XPM in a straight line configuration in almost the whole C-band. The converted signal is subsequently transmitted over 80-km conventional single-mode fiber (SMF) and 12-km dispersion compensating fiber (DCF) without noteworthy eye diagram degradation and penalty.

II. Experiment Setup

The experimental setup is shown in Fig. 1. The control laser is a 10-GHz 1560-nm erbium fiber ring laser (EFRL) that generates 2.3-ps full-width at half-maximum (FWHM) pulses. After adding the $LiNbO_3$ modulator, and modulating the control pulses with a pseudorandom bit sequence (PRBS) of $2^{31}-1$, a control signal at 10 Gb/s is obtained. The time–bandwidth product is 0.4; this shows that the chirp of the converted pulse is very small. Then the 10-Gb/s control signal is passively multiplexed up to 80 Gb/s using a fiber interleaver. The continuous-wave (CW) lightwave is generated by a tunable external cavity laser. The 80-Gb/s control signal combined with the CW lightwave are amplified by an erbium-doped fiber

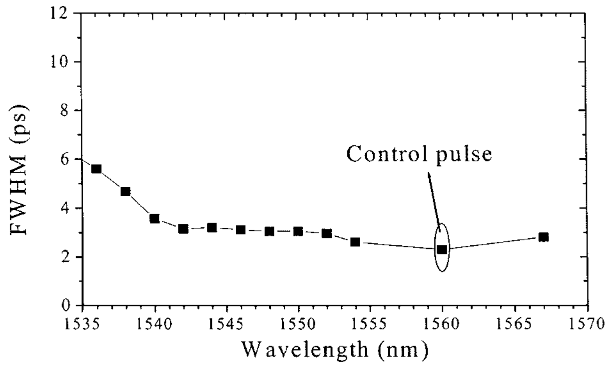

Fig. 2. Measured FWHM pulsewidth of the converted pulse as a function of wavelength.

amplifer (EDFA) and then injected into 1-km HNL-DSF. The HNL-DSF has a nonlinear coefficient of 10.9 $W^{-1}\cdot km^{-1}$, zero dispersion wavelength of 1552 nm and dispersion slope of 0.022 ps/nm^2/km. The power of the 80-Gb/s control signal into the HNL-DSF is 18.5 dBm and the CW lightwave power is 8 dBm. The 1.5-nm bandpass tunable optical filter at the output of the HNL-DSF is used to suppress the control signal and CW lightwave. A NOLM is used to demultiplex the 80-Gb/s OTDM signal to a 10-Gb/s signal and the control pulse is also obtained from the EFRL. The NOLM consists of 3-km common DSF with a zero-dispersion wavelength of 1555 nm, dispersion slope of 0.06 ps/nm^2/km and nonlinear coefficient of 2.6 $W^{-1}\cdot km^{-1}$. The transmission span includes 80-km conventional SMF and 12-km DCF; the DCF is used to fully compensate the accumulated dispersion of the SMF near 1550 nm.

III. Experimental Results

The measured pulsewidths of the converted pulses at 10 GHz as a function of the wavelength of the CW lightwave are shown in Fig. 2. The pulsewidths of the converted pulses from 1540 to 1568 nm are almost constant at 3 ps. Slightly broadened pulse is caused by the limited bandwidth of the optical filter; a 2.3-ps FWHM pulse will be broadened to approximately 3 ps when the filter bandwidth is 1.5 nm. When the CW lightwave wavelength is 1535 nm, the pulsewidth of the converted signal is smaller than 6 ps. For an 80-Gb/s signal, the intersignal interference (ISI) is small when the pulsewidth is 6 ps; this demonstrates that 80-Gb/s wavelength conversion can be realized in the whole C-band by use of 1-km HNL-DSF. For a 160-Gb/s OTDM signal, the FWHM pulsewidth of the converted signal should be equal to or smaller than 3 ps in order to overcome ISI; our results suggest that 160-Gb/s wavelength conversion can be realized in the wavelength range from 1540 to 1568 nm because the pulsewidth of the converted signal can be kept sufficiently small.

For a CW laser wavelength of 1545.6 nm, the bit-error-rate (BER) performance of the converted signal is measured and shown in Fig. 3. Compared with the 10-Gb/s back-to-back signal at 1560 nm, the power penalty after wavelength conversion and demultiplexing at a BER of 10^{-9} is 4.2 dB where about 2 dB is caused by wavelength conversion in the HNL-DSF and about 2.2 dB by demultiplexing in the NOLM. The optical spectra

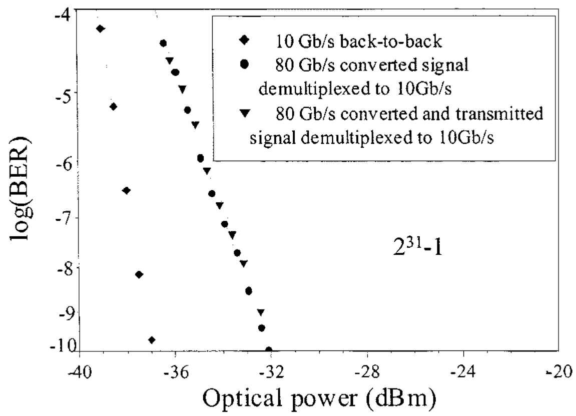

Fig. 3. BER curves as a function of received power.

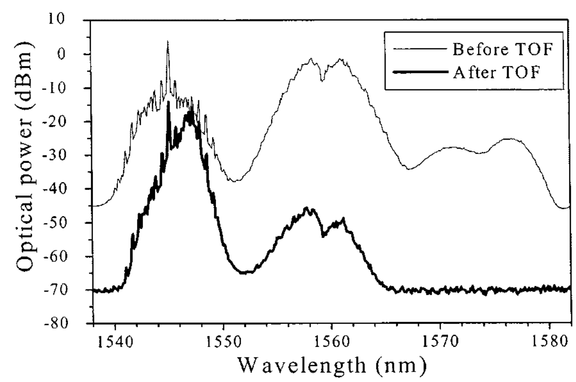

Fig. 4. Optical spectra before and after tunable optical filter.

at the output of the 1-km HNL-DSF and after the filter behind the HNL-DSF are shown in Fig. 4. The converted signal exhibits over 25 dB (in 0.1 nm resolution) optical signal-to-amplified spontaneous emission (ASE) ratio. The filtered center wavelength of the converted signal is 1547.8 nm; which is 1.2 nm away from the input CW lightwave. Because a HNL-DSF is used parametric wavelength conversion easily occurs; hence, small four-wave mixing (FWM) signal at 1575 nm is generated by the strong control signal at 1560 nm and the converted signals at 1546 nm. The eye diagrams of the control signal at 1560 nm, converted signal at 1545.6 nm and demultiplexed signal at 1545.6 nm measured by a 50-GHz photodiode are shown in Fig. 5(a)–(c). Excellent eye diagram of the converted signal is obtained. Changing the ECL wavelength, Fig. 6(a)–(c) displays the eye diagrams of the converted signal at different wavelengths as measured by the 50-GHz photodiode. There is no obvious difference when the wavelength of the converted signal is larger than 1540 nm. When the wavelength of the converted signal is 1535 nm, the eye diagram is not very clear because of broadened pulsewidth as shown in Fig. 2 and increasing ASE noise of the EDFAs at this wavelength. We have only measured BER performance at 1545.6 nm. For other wavelengths, different penalties will be obtained when the converted signal is demultiplexed in the NOLM due to different walkoff time between the converted signal and the control pulse. However, the eye diagrams have been measured at various wavelengths. The converted signal at 1545.6 nm is transmitted over 80-km SMF and 12-km DCF. The measured eye diagram is shown in Fig. 5(c); a clear and open eye

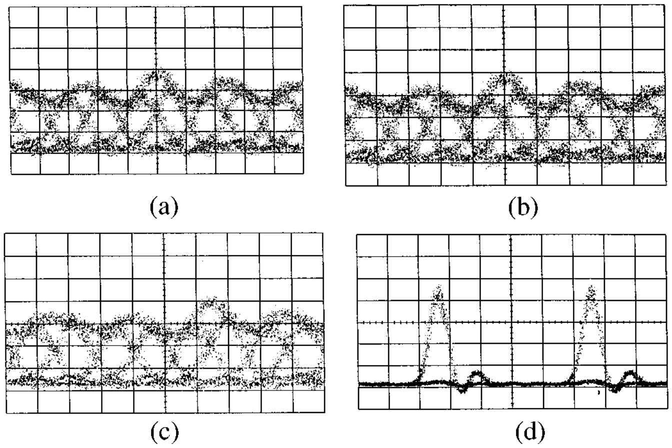

Fig. 5. Eye diagrams. (a) 80-Gb/s control signal at 1560 nm. (b) 80-Gb/s converted signal at 1545.6 nm. (c) 80-Gb/s converted signal at 1545.6 nm and transmitted over 80-km SMF and 12 km DCF. (d) 10-Gb/s demultiplexed signal without transmission.

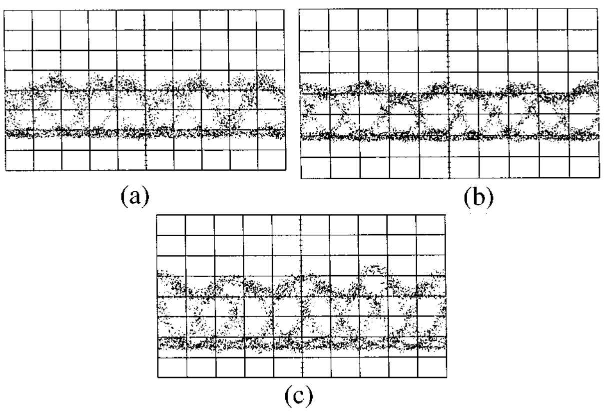

Fig. 6. Converted signals. (a) 1535 nm. (b) 1540 nm. (c) 1550 nm.

diagram is obtained. The measured BER performance is also shown in Fig. 3 and no noticeable penalty can be observed.

IV. Discussion

A possible problem is that the high-speed signal will be distorted if the control signal wavelength is located at or near the zero-dispersion wavelength of the HNL-DSF. Because of the large input control signal power and the strong nonlinear effect in the HNL-DSF, a super-continuum spectrum will be generated. The super-continuum spectrum will be added to the converted signal and this will lead to a situation where the converted signal can not be effectively separated from the super-continuum spectrum. When the input signal repetition frequency is not very high, for example, smaller than 40 Gb/s, one can overcome this problem. The CW lightwave can be removed and wavelength conversion can instead be realized by slicing the super-continuum spectrum [10]. However, if the input signal repetition frequency is higher, for example 80 Gb/s, even if the CW lightwave is removed, the short pulse control signal will be distorted because of the strong nonlinear effect in the fiber, and then it is not easy to realize wavelength conversion by slicing the super-continuum spectrum. Up to now, no 80-Gb/s super-continuum spectrum has been reported. In such a case, we must choose a proper HNL-DSF and keep the zero dispersion wavelength of the HNL-DSF away from the input signal wavelength. For example, for C-band signal wavelength conversion, we can choose the zero dispersion wavelength of the HNL-DSF to be near 1570 nm.

V. Conclusion

80-Gb/s pulsewidth-maintained wavelength conversion based on XPM in a 1-km HNL-DSF and subsequent filtering by a TOF has been demonstrated. The converted signal is subsequently transmitted over 80-km conventional SMF and 12-km DCF without noteworthy eye diagram degradation and penalty.

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